Application of CSA Whole Spacecraft Isolation Systems to the Hubble Robotic Servicing Mission

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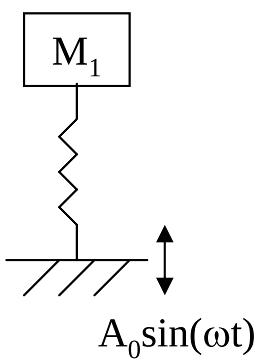
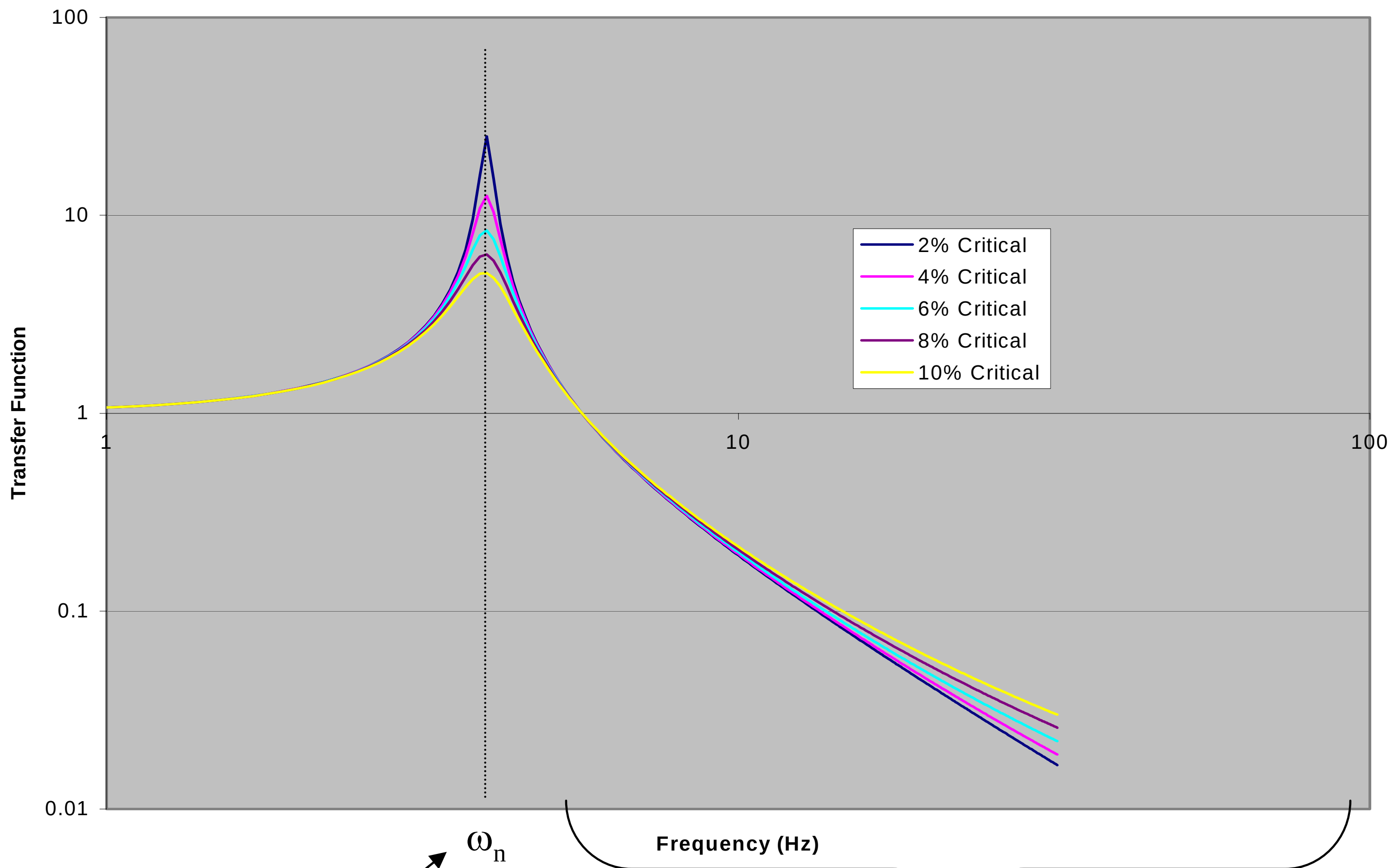
Background

- Isolation Systems are relatively new to spacecraft.
  - Spacecraft are generally hard-mounted to the launch vehicle adapter.
  - Six missions have been flown on Taurus and Minotaur Vehicles using whole spacecraft isolation systems built by CSA Engineering, Inc.
    - **Taurus:** GFO in February 1998, STEX in October 1998, MTI in March 2000, and QuickToms/Orbview-4 in August 2001
    - **Minotaur**: JAWSAT in January 2000 and MightySat in July 2000
- Isolation Systems have been used by the HST Program on all four Servicing Missions to date (SM1, SM2, SM3A, & SM3B), but only for component isolation

Isolation Concepts - Transmissibility



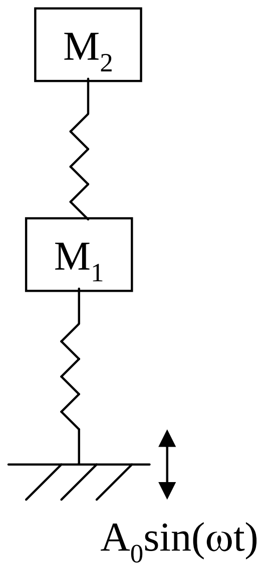


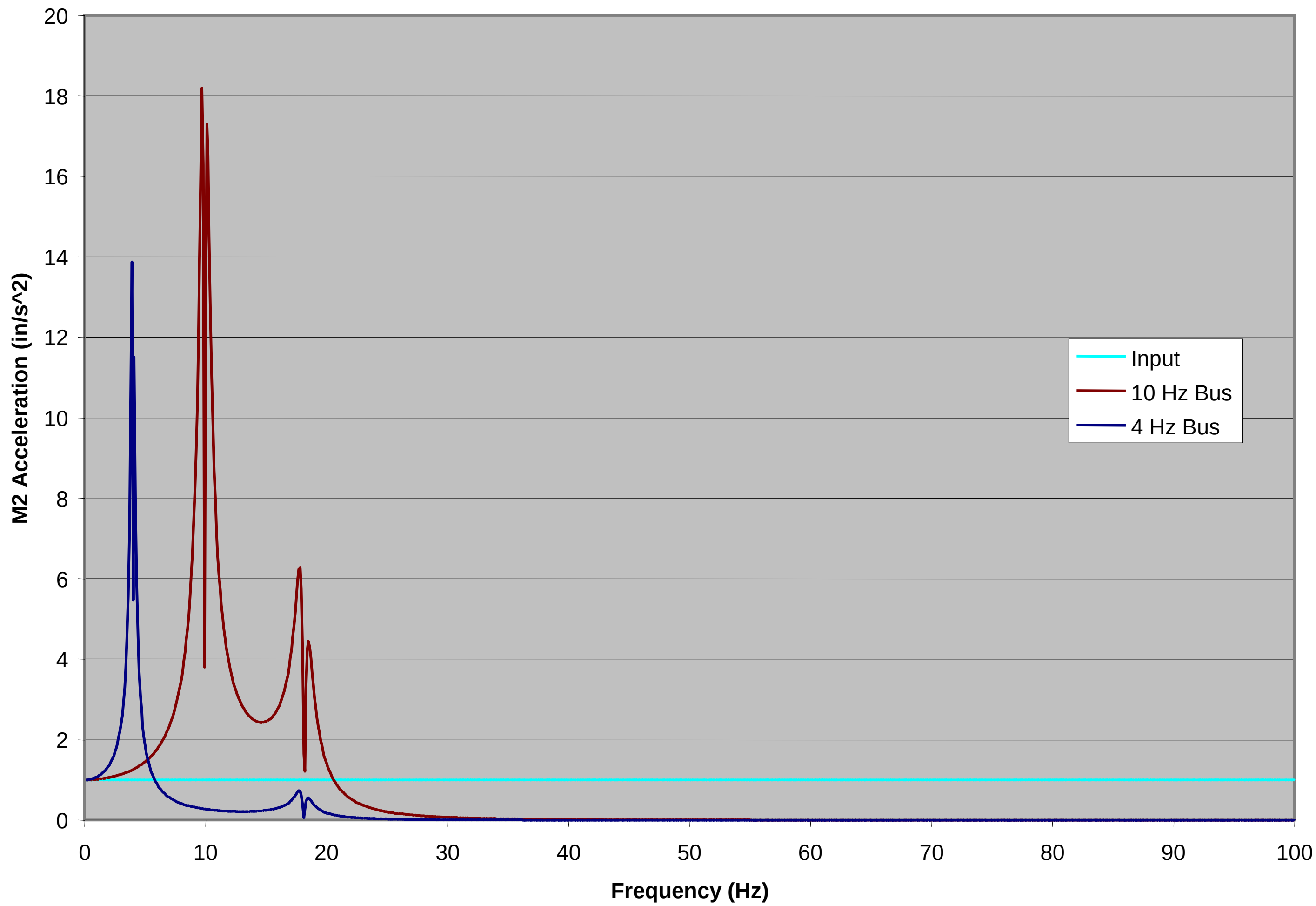
Isolation Frequency

Isolated Region

For components with resonant frequencies above the isolation frequency, dynamic flight loads are not transmitted through the isolation system

Importance of Mode Separation



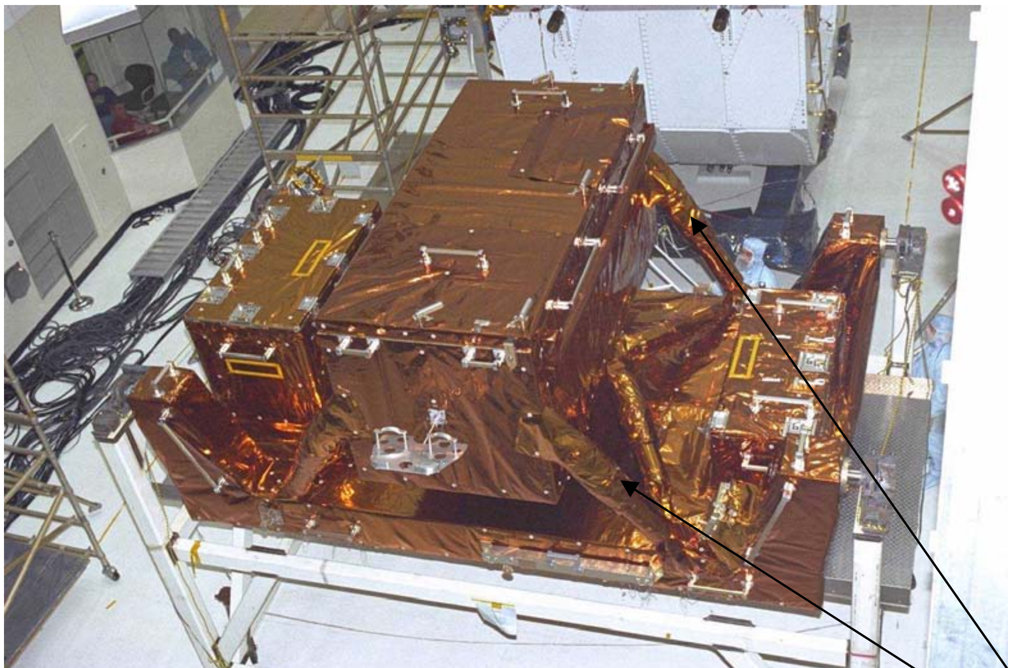


Component (M2) response at its resonance (18 Hz) is greatly reduced as the isolation frequency is lowered from 10 to 4 Hz

Past Use of Isolation Systems

Past HST Missions – SM2

Flight Configuration

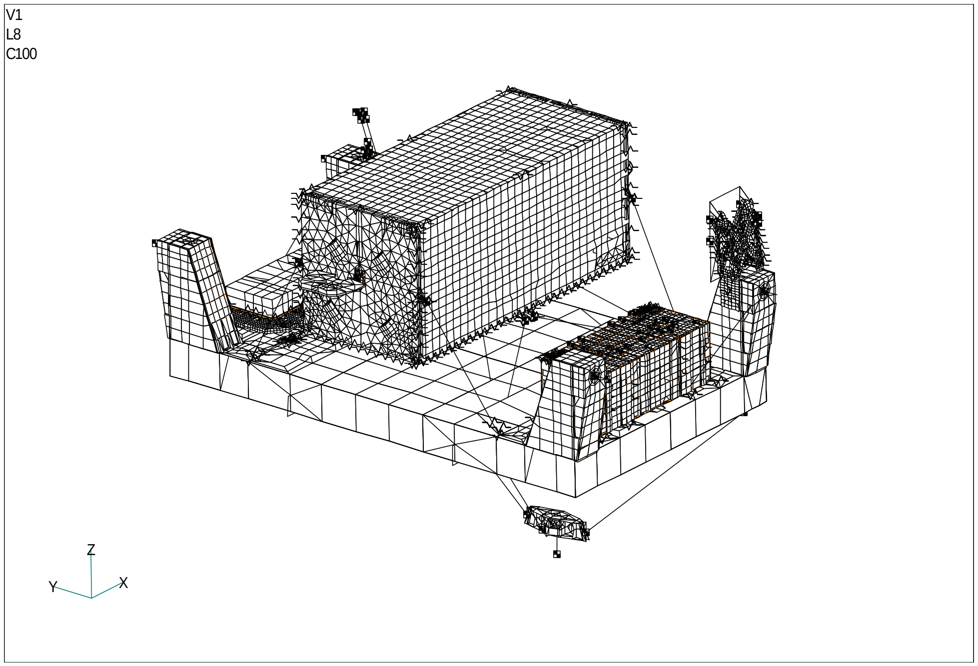


Test Configuration of Isolation System

M-Strut Spring-Dampers

Second Axial Carrier (SAC) carried the NICMOS Instrument for HST SM2 and the Advanced Camera for Surveys (ACS) for HST SM3B.

SAC Analytical Model



Modal Effective Mass About Model CG

HST SM3B SAC LIFTOFF ILC Model

Mode No.	Freq Hz	Damping %	X Dir	Y Dir	Z Dir	RX Dir	RY Dir	RZ Dir
1	1.94	8.0	0	1362	2	2.93E+05	3.37E+02	3.89E+04
			0.00%	*27.80%*	*0.00%*	*1.90%*	*0.00%*	*0.20%*
2	3.01	10.6	1463.2	0.1	2	3.20E+01	2.44E+06	8.10E+01
			29.10%	*0.00%*	*0.00%*	*0.00%*	*26.00%*	*0.00%*
3	3.9	13.7	4.6	5.2	1794.4	1.40E+03	3.81E+04	2.86E+03
			0.10%	*0.10%*	*36.60%*	*0.00%*	*0.40%*	*0.00%*
4	4.32	15.1	0.2	2.8	1.9	1.34E+04	4.58E+03	2.42E+06
			0.00%	*0.10%*	*0.00%*	*0.10%*	*0.00%*	*13.10%*
5	5.46	19.1	0.6	415.1	4.4	1.56E+06	1.02E+03	9.00E+00
			0.00%	*8.50%*	*0.10%*	*10.20%*	*0.00%*	*0.00%*
6	5.98	21.0	294.6	0.7	1.7	2.51E+03	1.07E+06	4.38E+03
			5.90%	*0.00%*	*0.00%*	*0.00%*	*11.40%*	*0.00%*
7	11.42	2.1	0	0.1	0	1.61E+02	1.90E+01	2.67E+02
			0.00%	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*
8	11.61	1.3	0	0.1	0	1.44E+02	1.40E+01	4.50E+02
			0.00%	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*
9	14.27	1.4	0.1	0	0.1	0.00E+00	1.67E+02	2.00E+00
			0.00%	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*
10	14.34	2.2	0.1	0	0	0.00E+00	2.41E+02	0.00E+00
			0.00%	*0.00%*	*0.00%*	*0.00%*	*0.00%*	*0.00%*
11	15.91	1.2	73.8	51.8	1233	1.85E+03	5.57E+03	3.29E+03
			1.50%	*1.10%*	*25.10%*	*0.00%*	*0.10%*	*0.00%*
12	17.74	1.4	65.4	2371.8	110	7.43E+04	1.05E+05	3.91E+05
			1.30%	*48.30%*	*2.20%*	*0.50%*	*1.10%*	*2.10%*
13	19	1.5	979.8	285.1	89.2	4.35E+03	1.74E+06	2.48E+05
			19.50%	*5.80%*	*1.80%*	*0.00%*	*18.60%*	*1.30%*

Characterized by 6 low frequency and highly damped “isolation” Modes, separated in frequency from the carrier modes

M-Strut Damping

- Isolator Damping is both temperature and frequency dependent

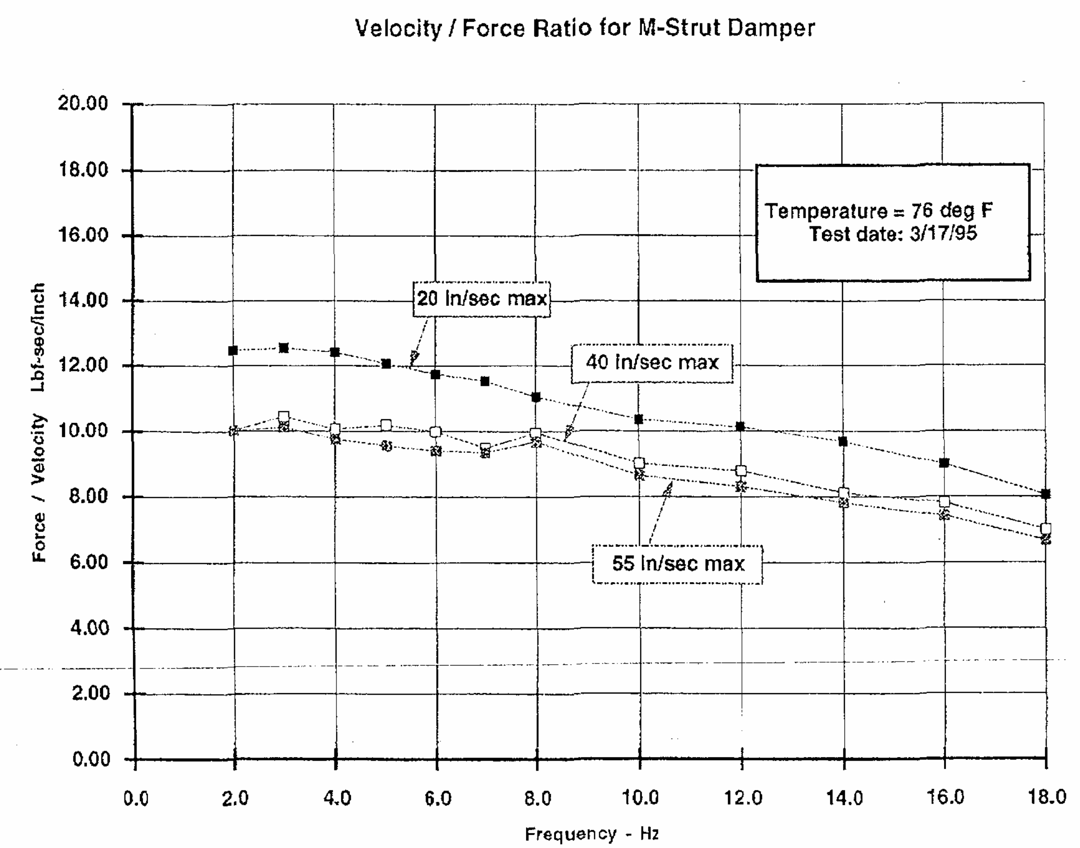
- Methodology was developed for HST SM2 (STS-82) whereby a conservative estimate of the isolator damping coefficient is used to develop an isolator damping matrix, $[\Phi^T_{sys}\ [C_{isol}]\ \Phi_{sys}]$

- This damping matrix (fully populated, non-diagonal) is added to the standard payload damping (modal damping / diagonal) to form a complete damping matrix for the payload

- The damping ratios for the first six isolation modes range (typically) from 8% to 25%

M-Strut Damping (cont.)

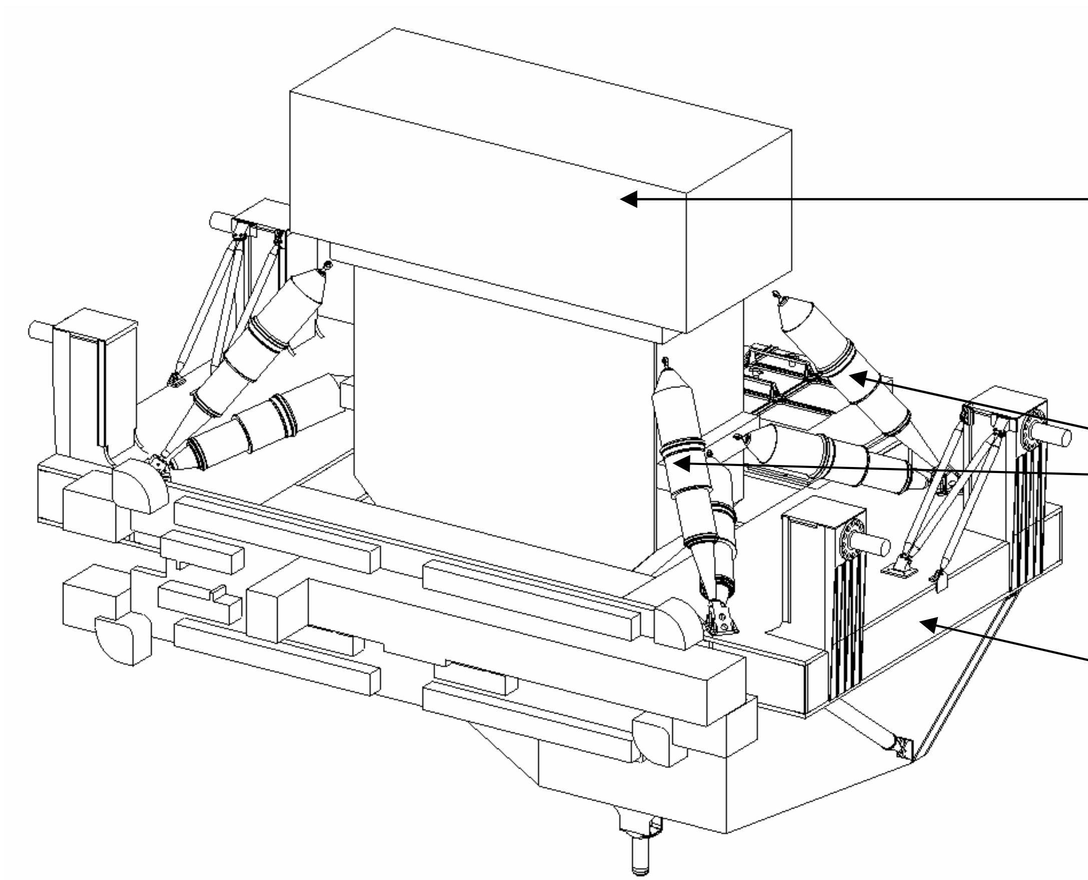
- Isolator damping (dashpot constant) is a function of temperature, frequency, and peak velocity, and comes from SM2 complex stiffness tests of the isolators



Past HST Missions – SM3A

- Orbital Replacement Unit Carrier (ORUC)
- Load isolated transportation for
    - Fine Guidance Sensor
    - Cosmic Origins Spectrograph
- Isolation achieved through the use of large leaf springs and sophisticated mechanism system

Past/Present HST Missions – SM4



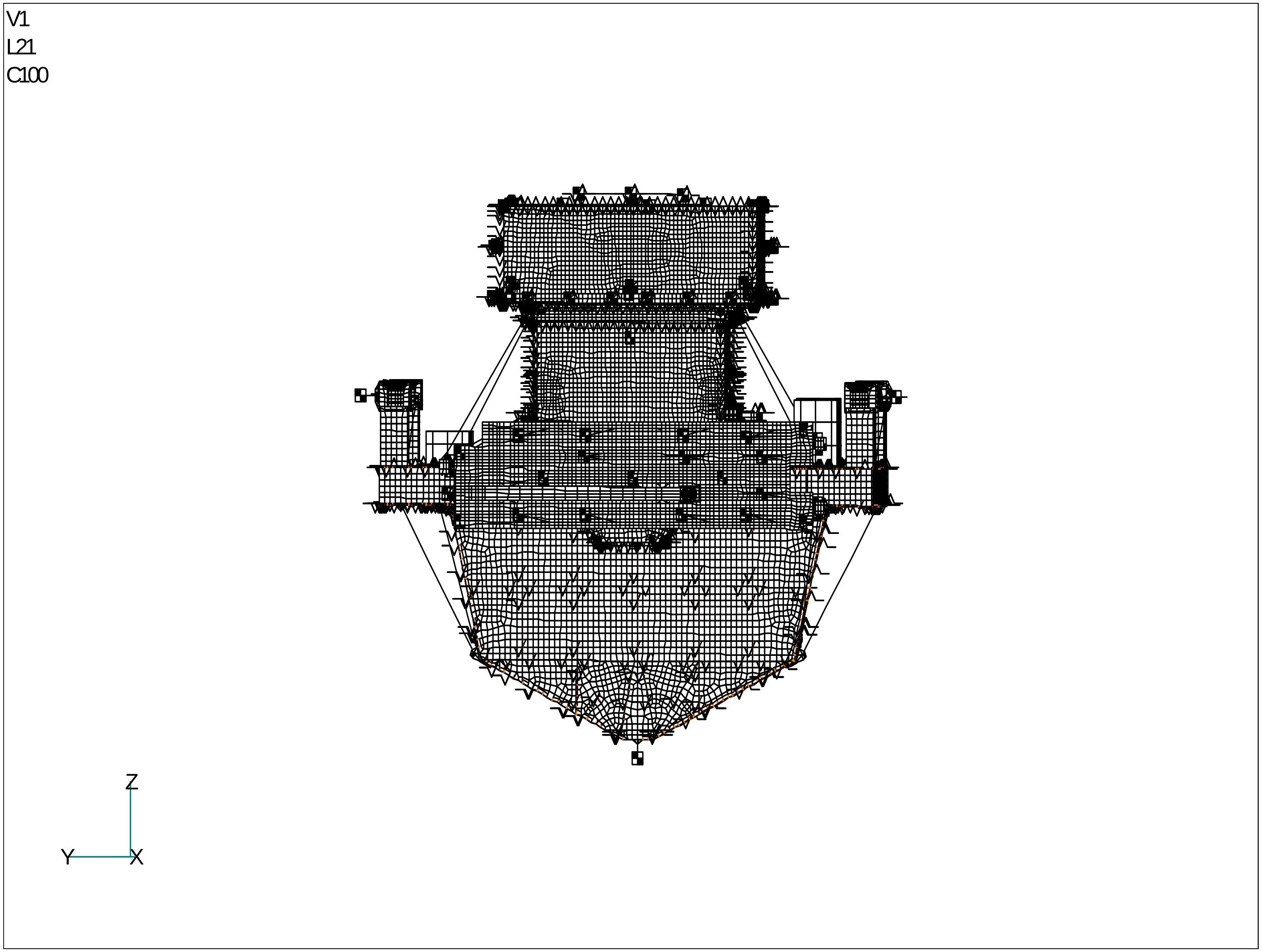
WSIPE contains new HST Camera

M-Strut Isolators

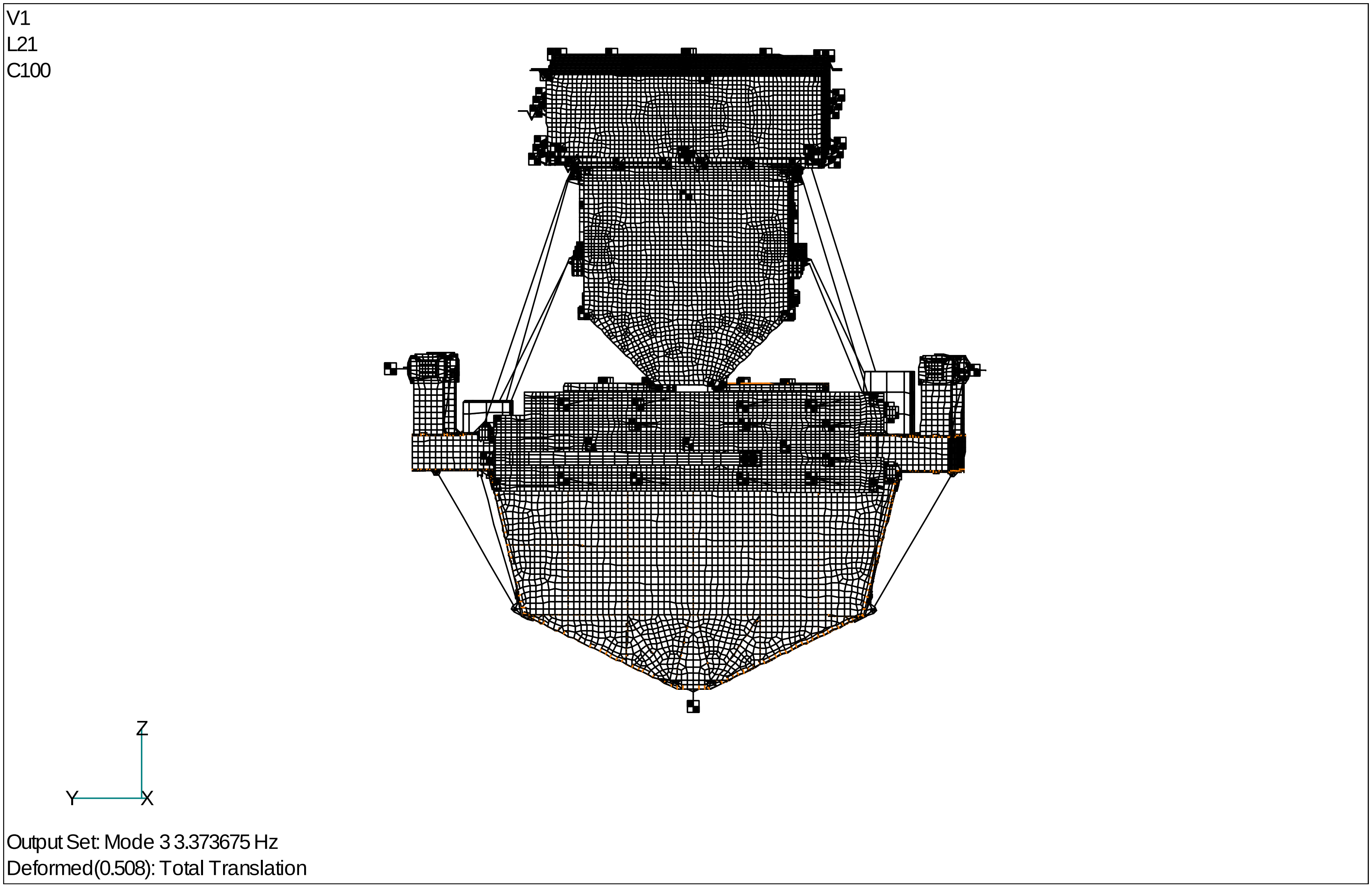
SLIC Pallet

SM4 Design re-uses M-strut isolators on a new Cross-bay shuttle carrier

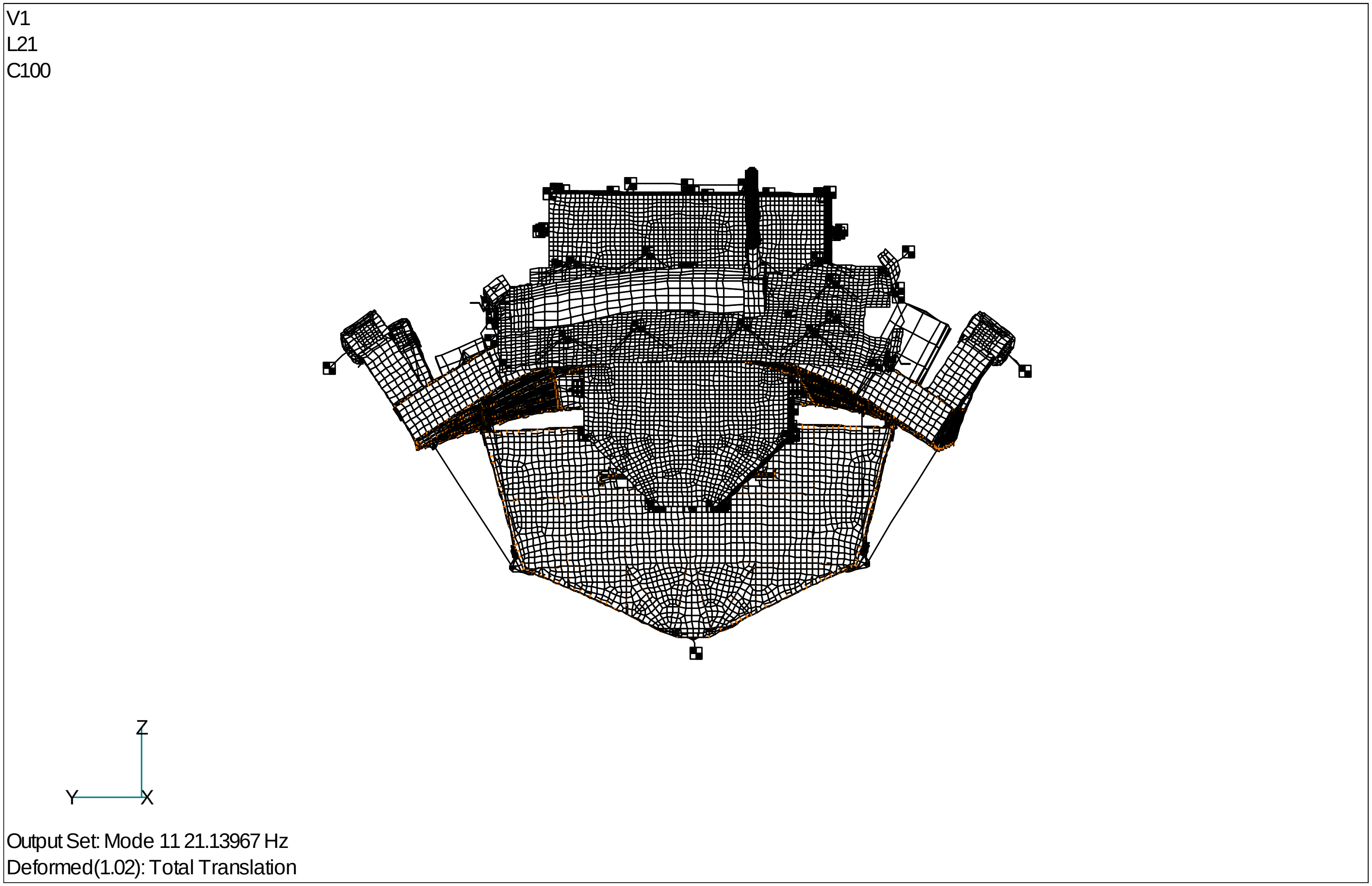
HST SM4 Example - SLIC



HST SM4 Example – Isolation Mode

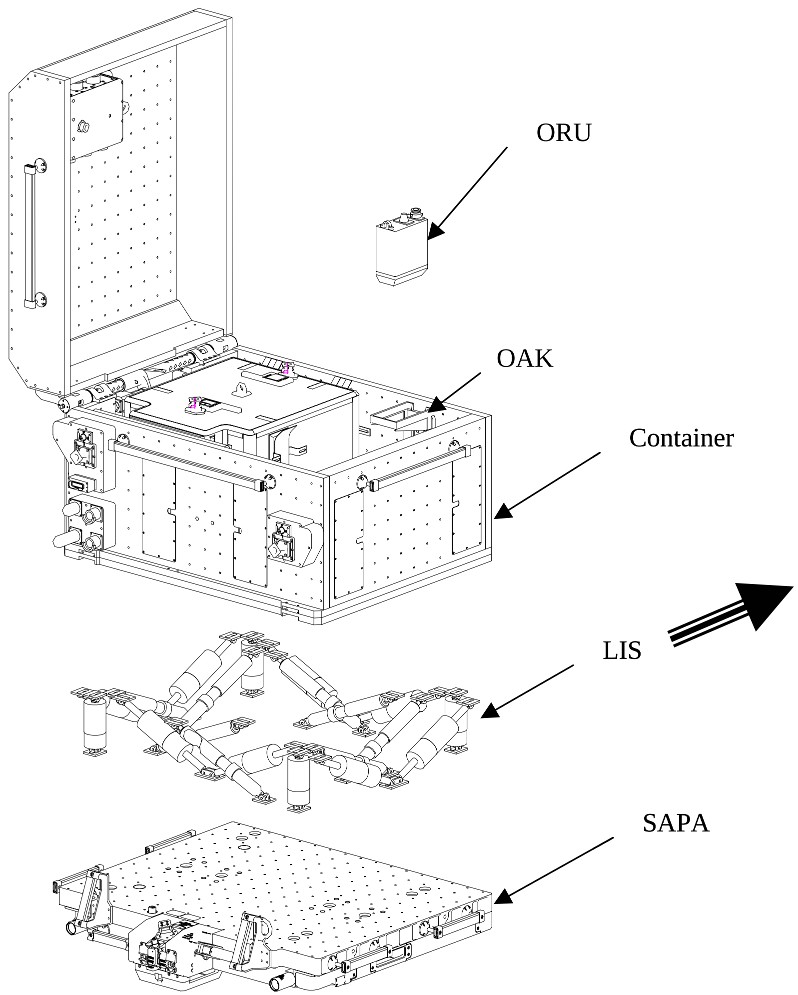


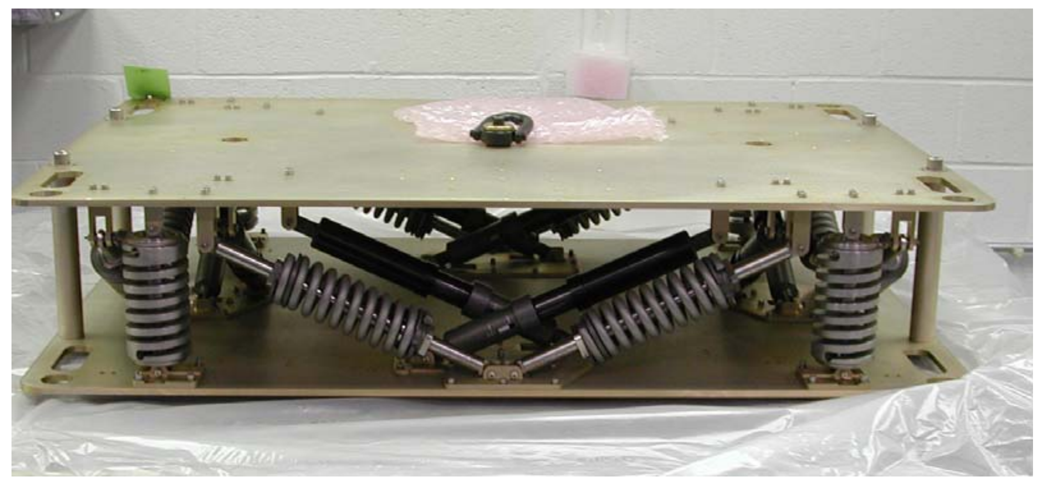
HST SM4 Example – Carrier Mode



Note that the isolated camera container (WSIPE) is stationary
At 21 Hz (the carrier mode).

CTC Program (ISS)





Behavior of Isolated Components

- Isolated Component Loads come from static Launch Vehicle accelerations and "isolation modes" only
  - Component resonances (in this case, 18 Hz) are isolated from the Launch Vehicle (in this case, the Space Shuttle)

- Breakdown of HST Camera (WFC3) Net-CG Acceleration into its constituent terms shows no vibration response at 18 Hz

LOAD DECOMPOSITION RESULTS (CUMULATIVE) - ABS PEAK VALUES

HST SM4 Loads Cycle SLIC (MUF=1.25) Liftoff

C-B Dof	WFC3 Net CG X Magnitude	WFC3 Net CG X Cum %	WFC3 Net CG Y Magnitude	WFC3 Net CG Y Cum %	WFC3 Net CG Z Magnitude	WFC3 Net CG Z Cum %
BA 1	1.058	34.16	0.285	72.01	0.000	0.00
BA 2	0.001	34.21	-0.051	59.22	0.012	0.53
BA 3	1.149	71.32	-0.253	4.89	0.000	0.53
BA 4	-0.004	71.20	-0.004	5.91	-0.019	0.30
BA 5	0.003	71.31	-0.044	17.09	0.050	1.85
BA 6	0.005	71.47	-0.018	21.59	0.010	2.29
BA 7	0.000	71.47	-0.300	97.39	0.000	2.29

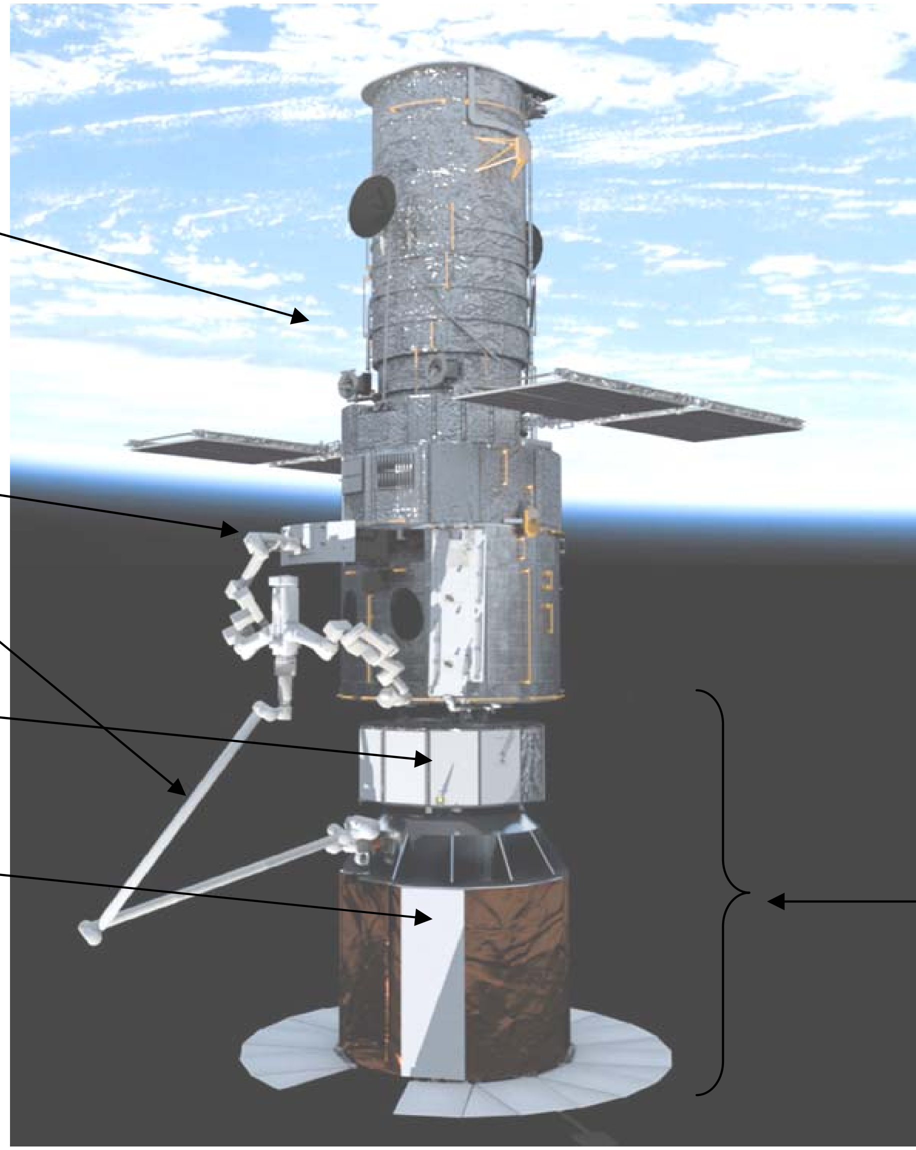
Mode No.	Freq Hz	WFC3 Net CG X Magnitude	WFC3 Net CG X Cum %	WFC3 Net CG Y Magnitude	WFC3 Net CG Y Cum %	WFC3 Net CG Z Magnitude	WFC3 Net CG Z Cum %
1	1.30	0.000	71.47	0.286	24.97	0.000	2.28
2	3.69	0.339	82.42	0.000	24.99	-0.130	3.34
3	3.79	0.099	85.63	0.001	24.84	-2.230	99.44
4	4.67	0.461	100.52	0.000	24.90	0.006	99.20
5	5.12	0.001	100.55	0.062	9.10	0.000	99.20
6	5.59	0.000	100.54	0.422	97.70	0.000	99.21
7	17.90	0.000	100.53	0.003	98.37	0.000	99.21
8	22.08	-0.004	100.39	0.000	98.37	-0.002	99.28
9	25.29	0.000	100.39	0.000	98.34	0.000	99.28
10	25.36	0.014	100.84	0.000	98.34	-0.003	99.41
11	26.12	-0.027	99.97	0.000	98.34	-0.015	100.05
12	26.45	0.000	99.97	0.000	98.34	0.000	100.05

Hubble Robotic Servicing

Overview of Mission & Spacecraft

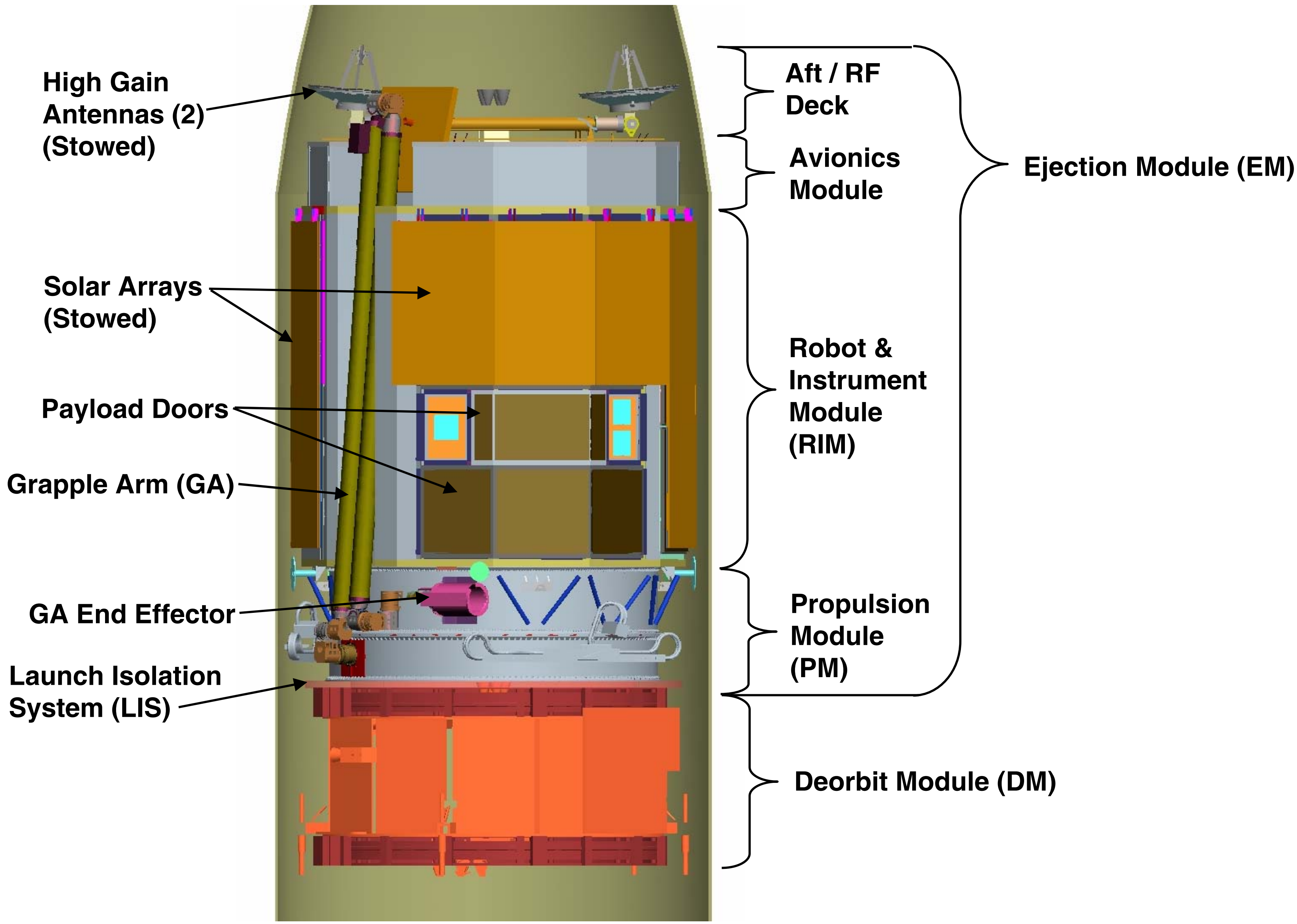
HRV Mission Configuration

- Hubble Space Telescope
- Robot System
- De-Orbit Module (DM)
- Ejection Module (EM)

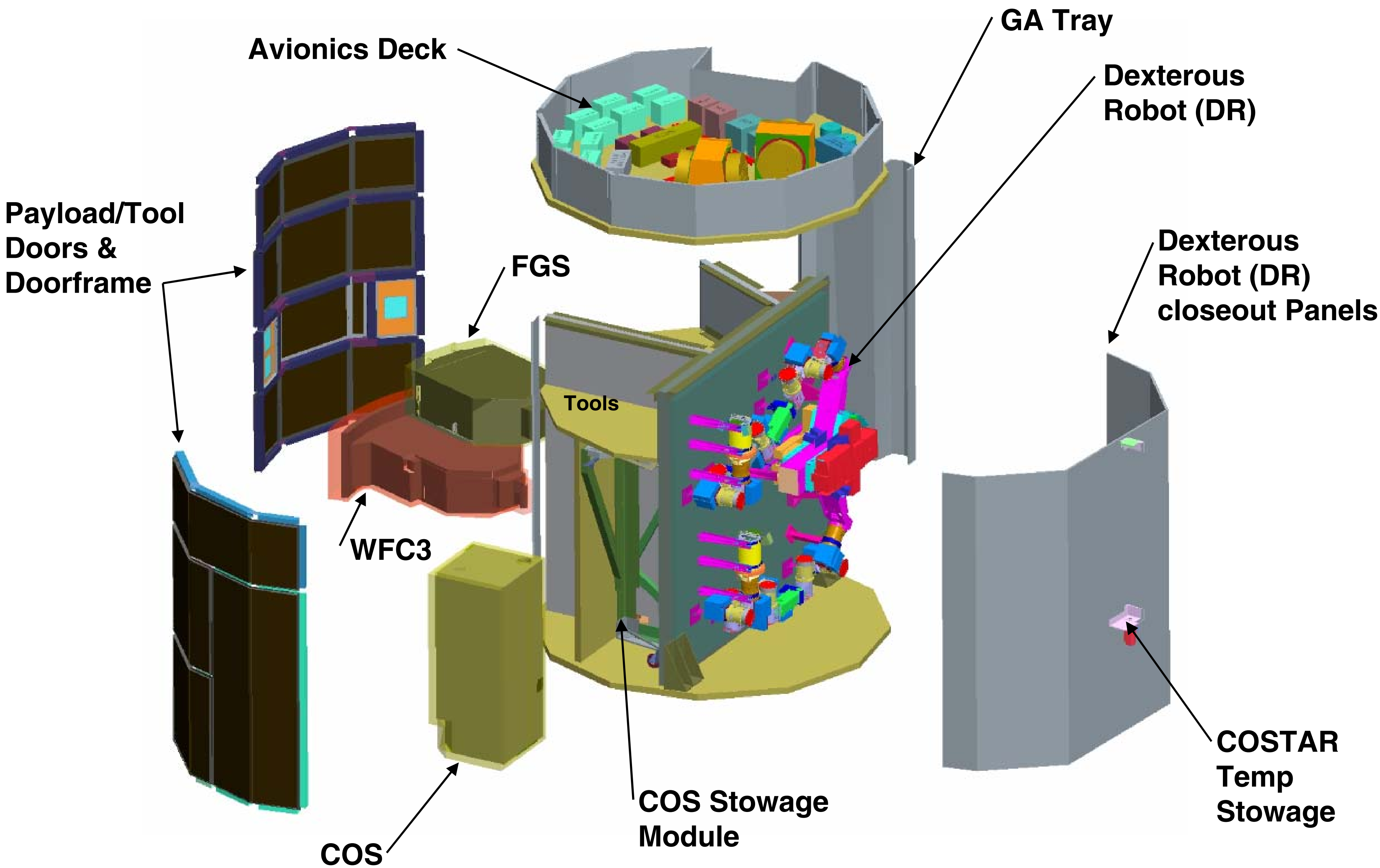


- HRV Spacecraft

HRV Launch Configuration



Architecture – EM RIM Expanded View



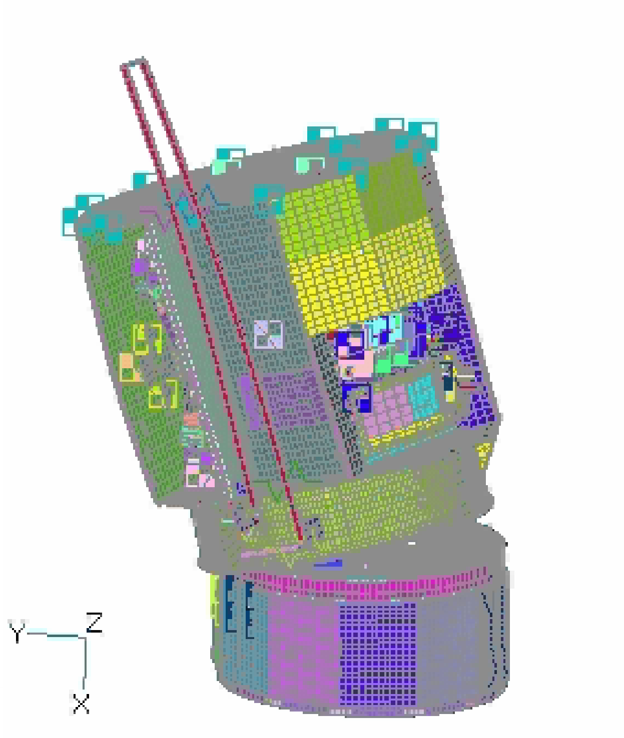
Hubble Robotic Servicing

Isolation System Development

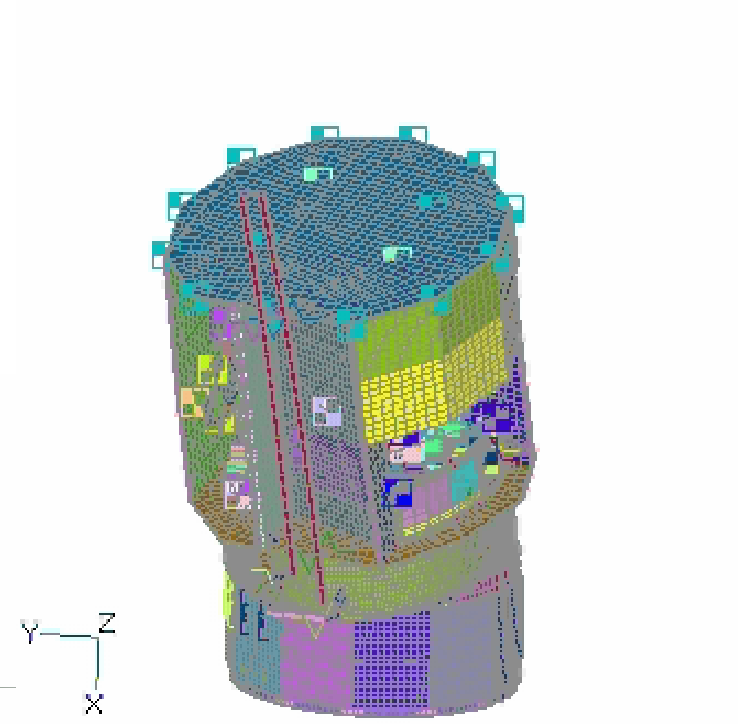
Isolation System Development

- For Pre-Qualified Science Instruments (COS, WFC3 & FGS) and Robot System (DR & GA), the HRV Program identified an early need for proactive management of launch loads
  - SI's previously qualified for shuttle launch on isolation systems
  - DR qualified for shuttle launch, but disassembled (no isolation). Joint Loads expected to be an issue.
- Packaging of Instruments and Robots forced a compromised EM structure design
  - EM structure would benefit from reduced loads
- Initial Loads Analysis showed greatly reduced DR joint loads with an isolation system.
  - "whole spacecraft" isolation was the only viable means of delivering isolation to the DR, due to its size.
- CSA Engineering was chosen to support concept development of an isolation system, since CSA has patented "whole spacecraft isolation system" designs

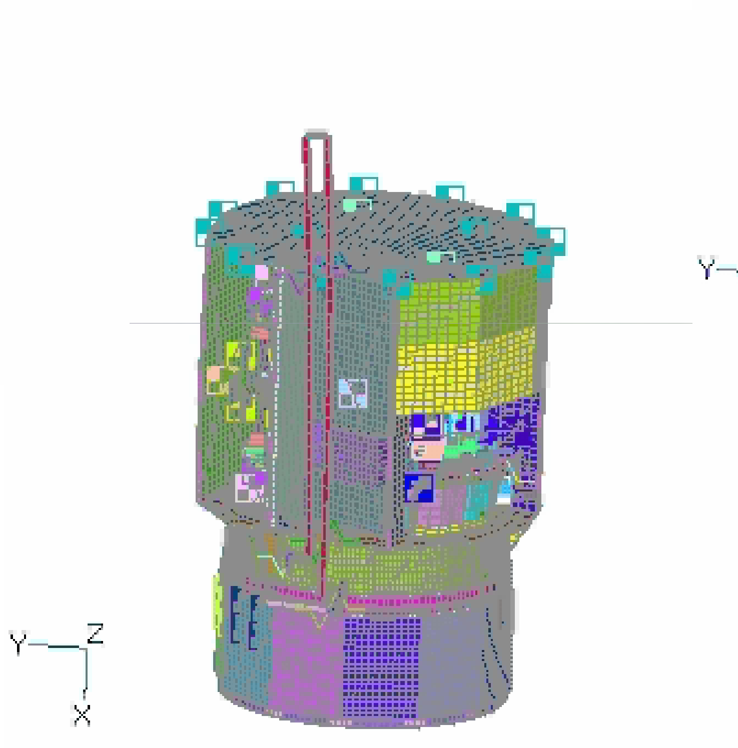
HRV Isolation System Frequencies



First Lateral Mode
(4 Hz)



Second Lateral Mode
(4.1 Hz)



First Axial Mode
(10 Hz)

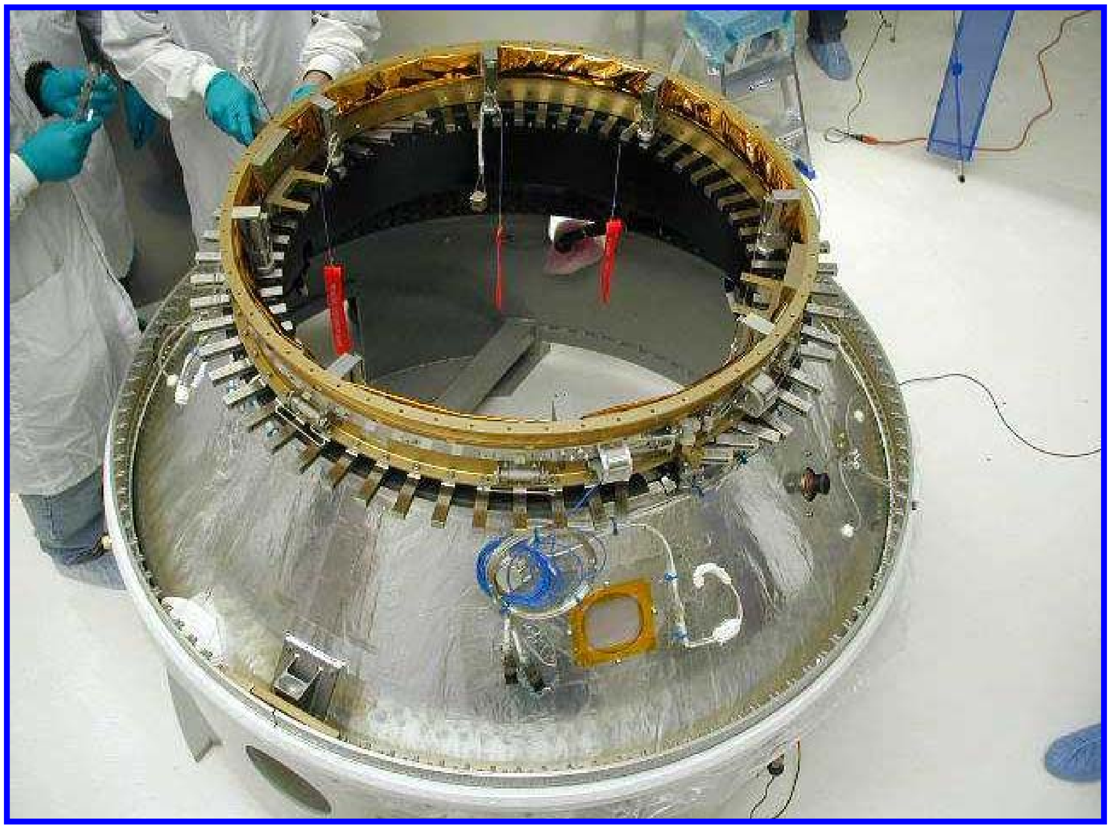
HRV Frequency Requirements

- HRV
  - First lateral mode goal: **4Hz**
  - First axial (bounce) mode goal: **10Hz**

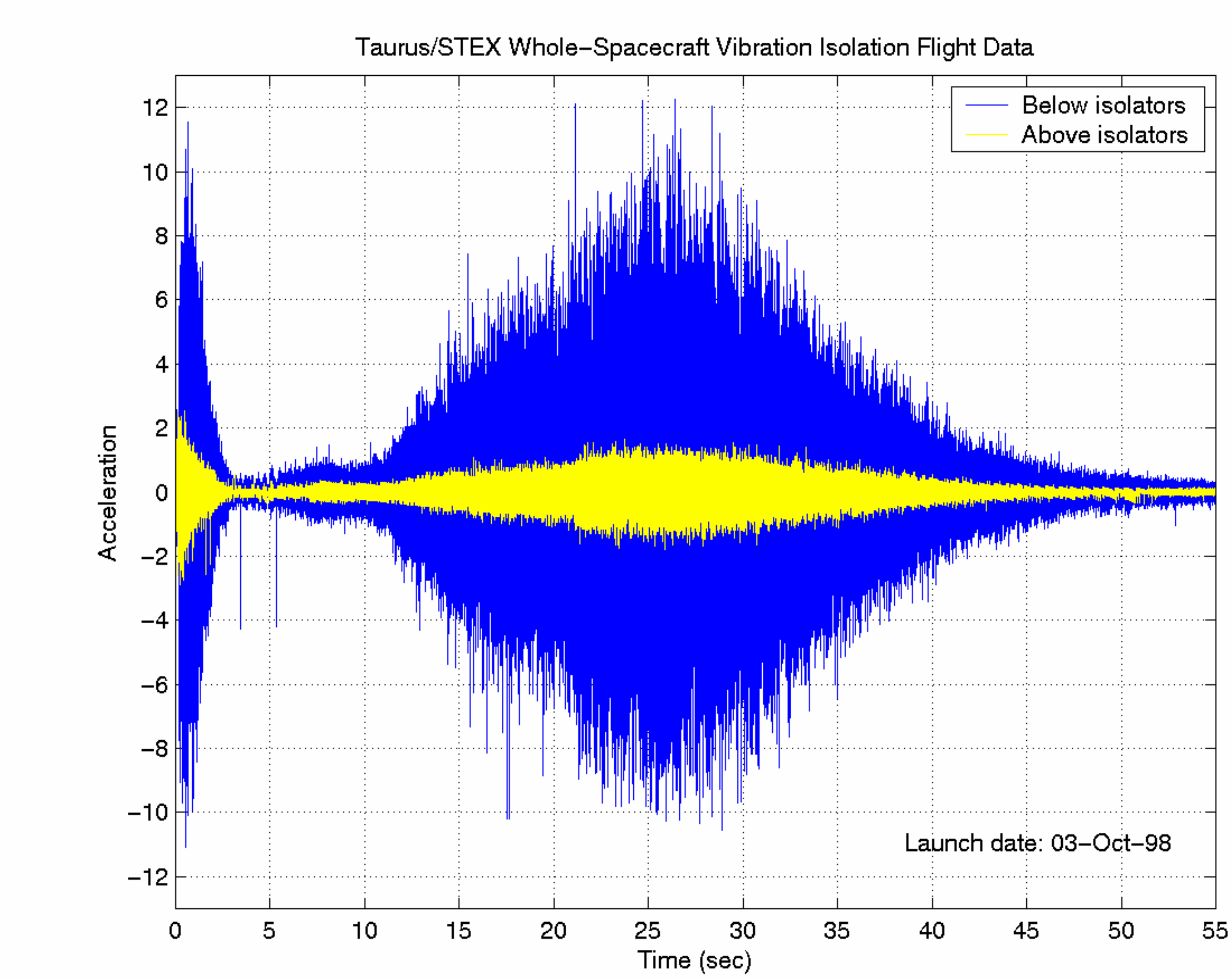
  "Isolation" Modes
- DM structure
  - First primary structural mode: **10Hz** with rigid EM mass attached
    - System level models show DM design is adequately stiff (more later)
- EM structure
  - First flexible, non-isolation mode goal: **20Hz**
  - Based on the EM being isolated at DM/EM interface

Taurus Class Isolation System

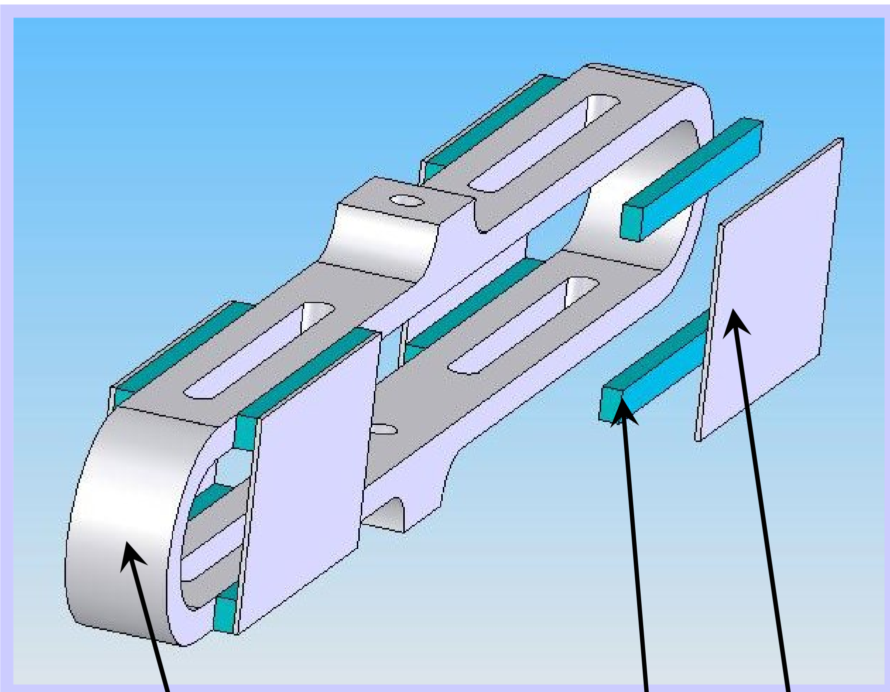
CSA Engineering, Inc.
Vibration, Precision Motion, and Noise Control

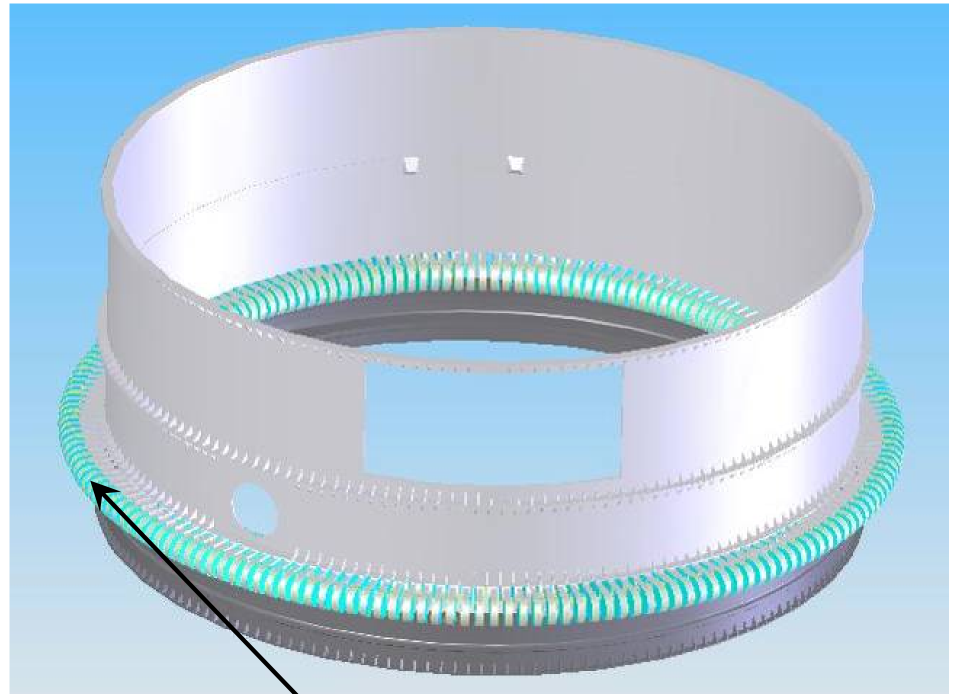


Actual Flight Data (Taurus – CSA Uniflex System)



HRV Isolation System Design - CSA Engineering





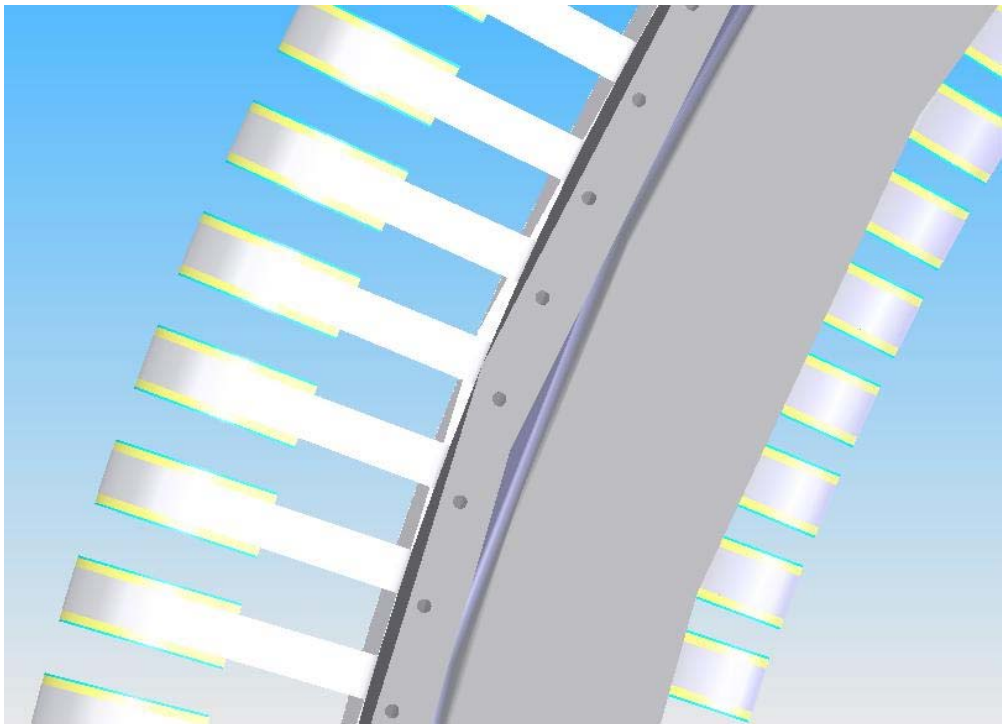
Flexure
Titanium 6Al4V

Viscoelastic Damping
3M ISD242

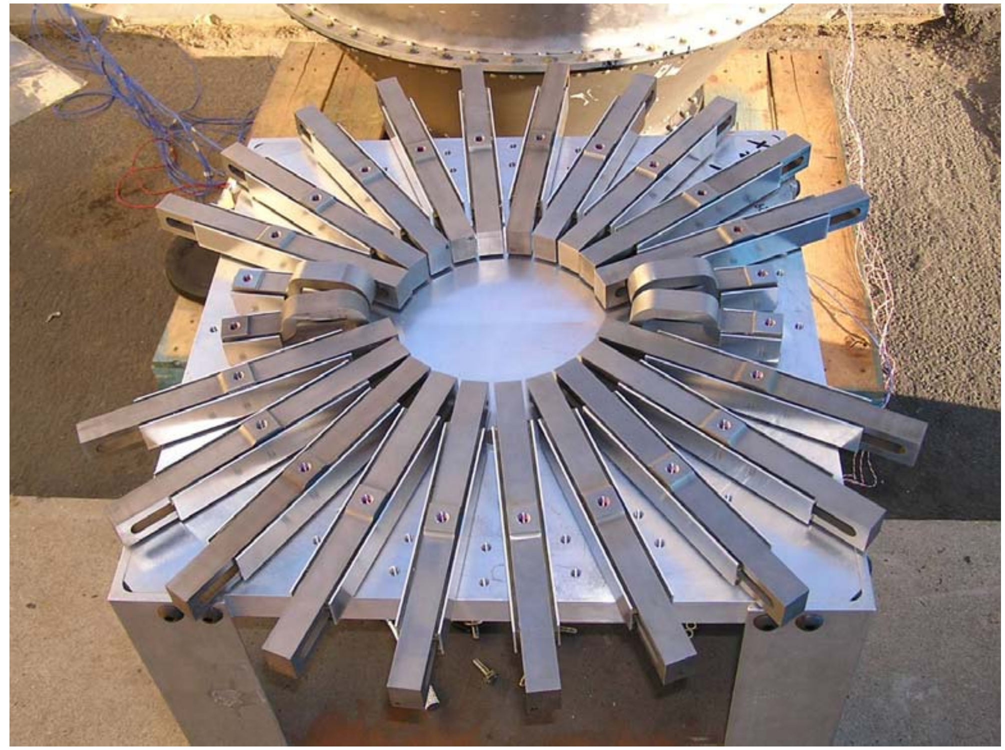
Constraining Layer
Aluminum 6061-T6

Isolators are Bolted between the EM and the DM, just above the Clamp Band

HRV Isolation System Design



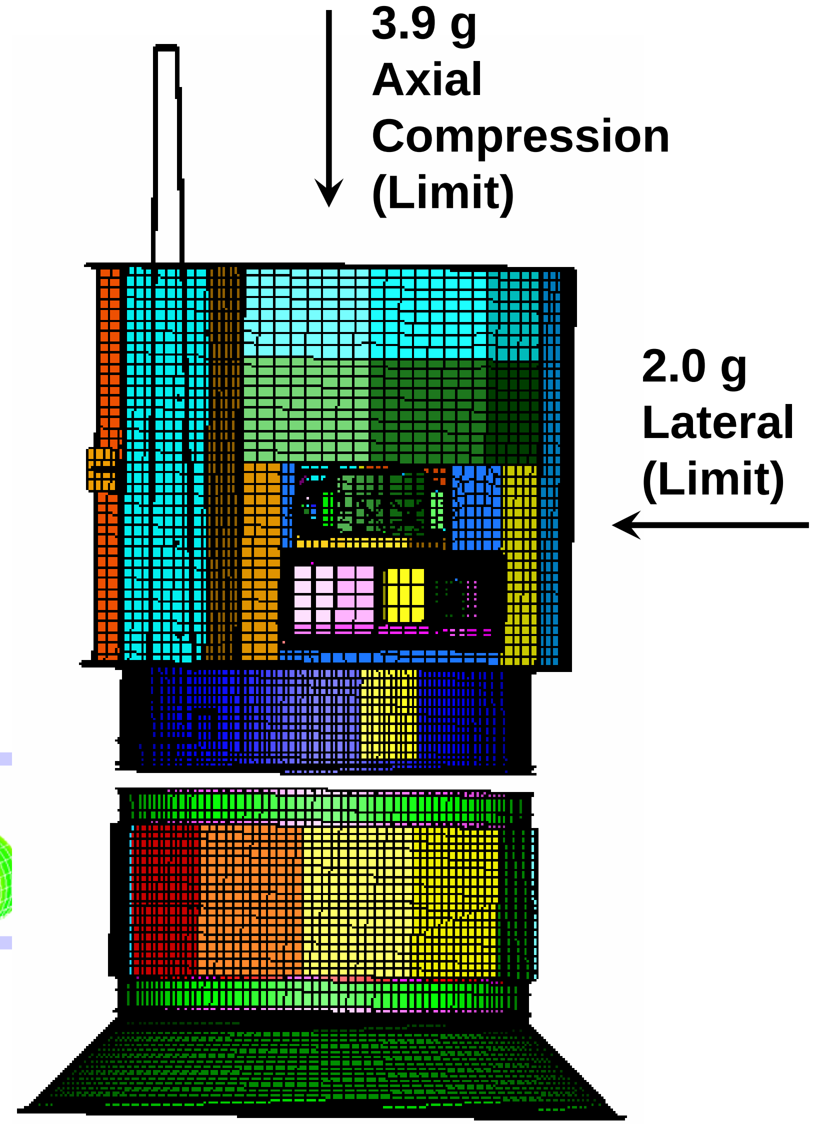
View of isolator spacing

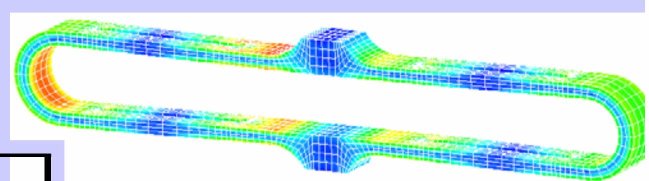


“half” isolators can be designed to accommodate grapple arm clearances

HRV Isolation System Design

- Isolation Design Parameters
  - Stiffness selected to give a 10 Hz axial "bounce" mode
    - Seen as the best compromise of load reduction and ease of implementation (stroke of isolators, clearance with shroud)
  - Strength evaluated using the EM primary structure design load cases
    - 2 g's lateral and 3.9 g's axial gives peak isolator loads





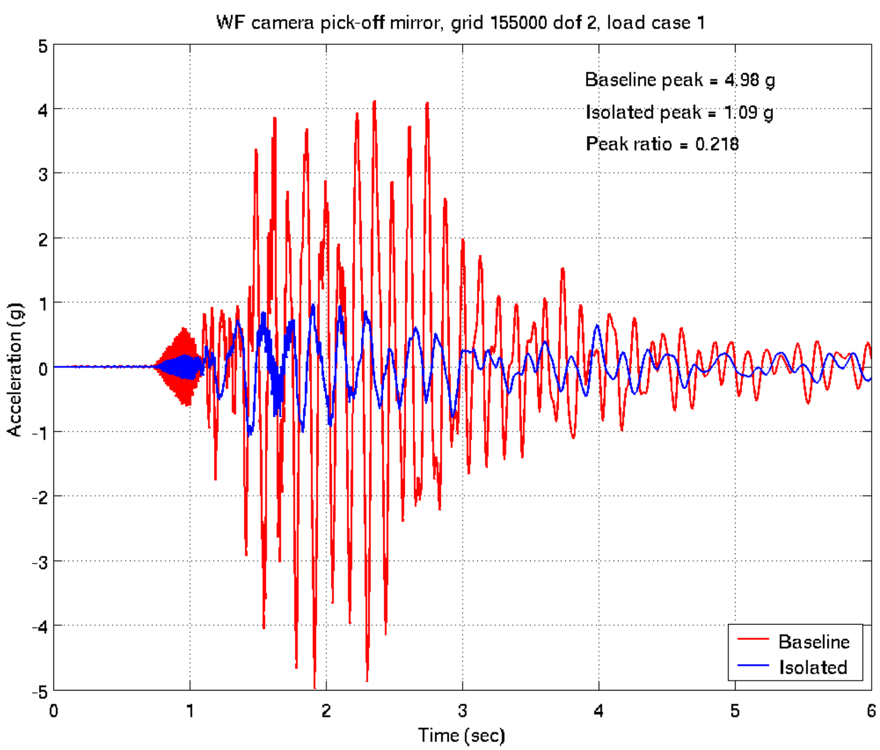
Fx (lb)	156.1
Fy (lb)	-32.0
Fz (lb)	-1109.3
Mx (in-lb)	-58.0
My (in-lb)	-696.1

Hubble Robotic Servicing

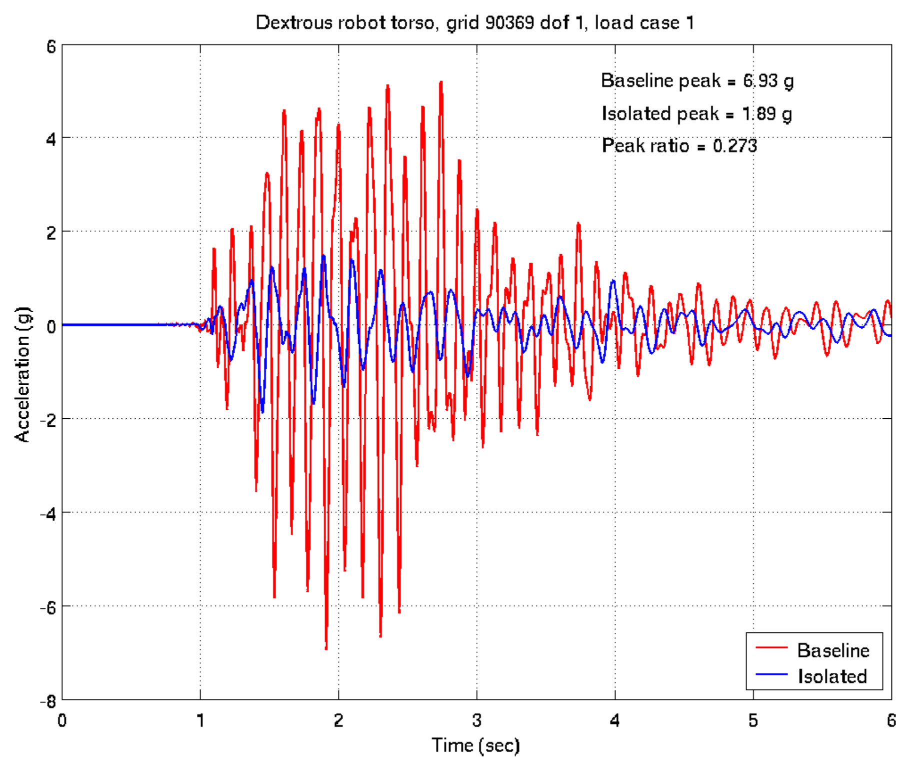
Loads Work Through PDR

*PREDICTED** HRV Flight Loads - Liftoff

Wide Field Camera Pick-Off Mirror



Dexterous Robot Torso

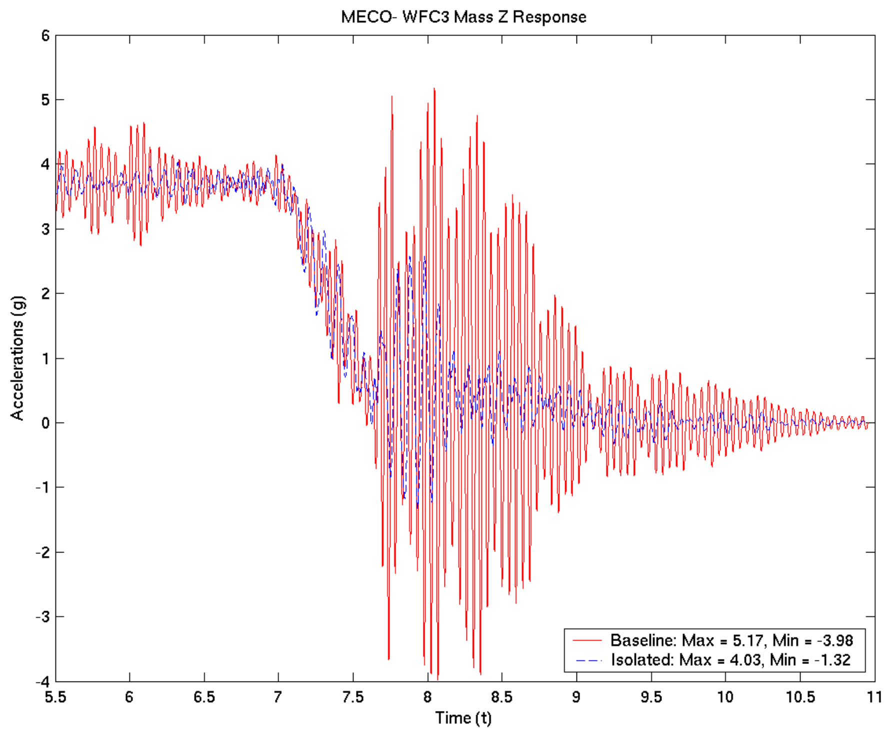


Isolation System Mitigates Liftoff Loads

* = Results shown for November 2004 Trade Study Model

*PREDICTED** HRV Flight Loads - MECO

Wide Field Camera CG Response

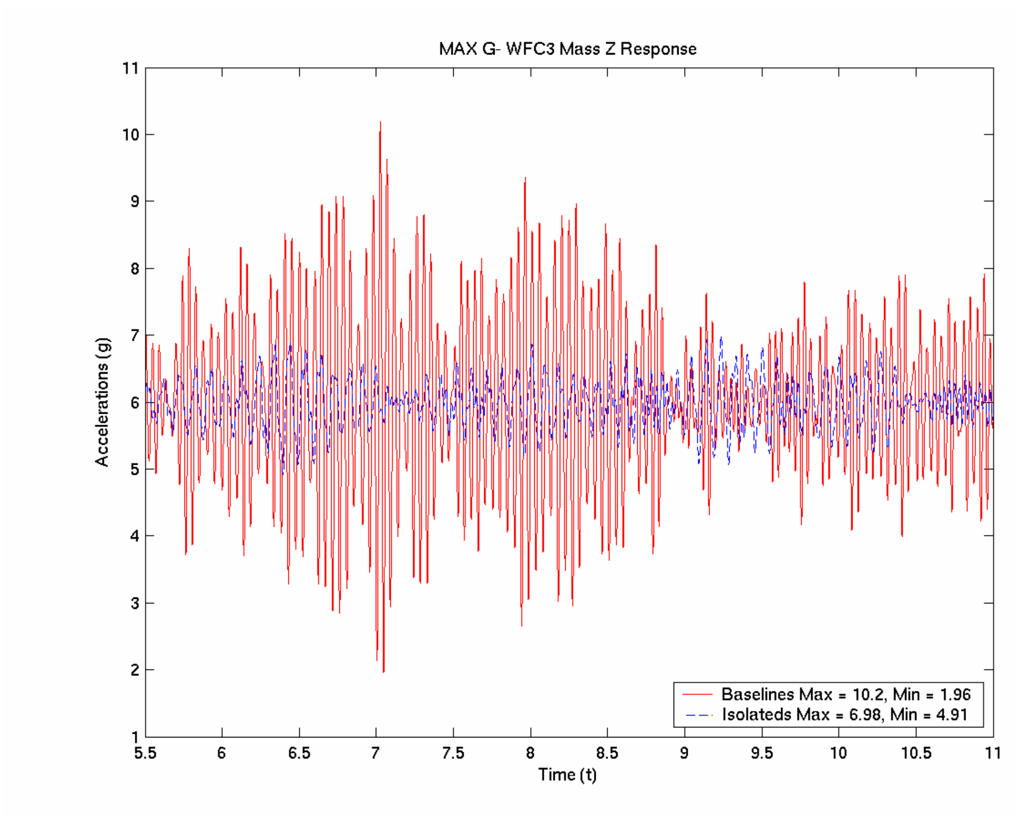


Isolation System Mitigates MECO Loads

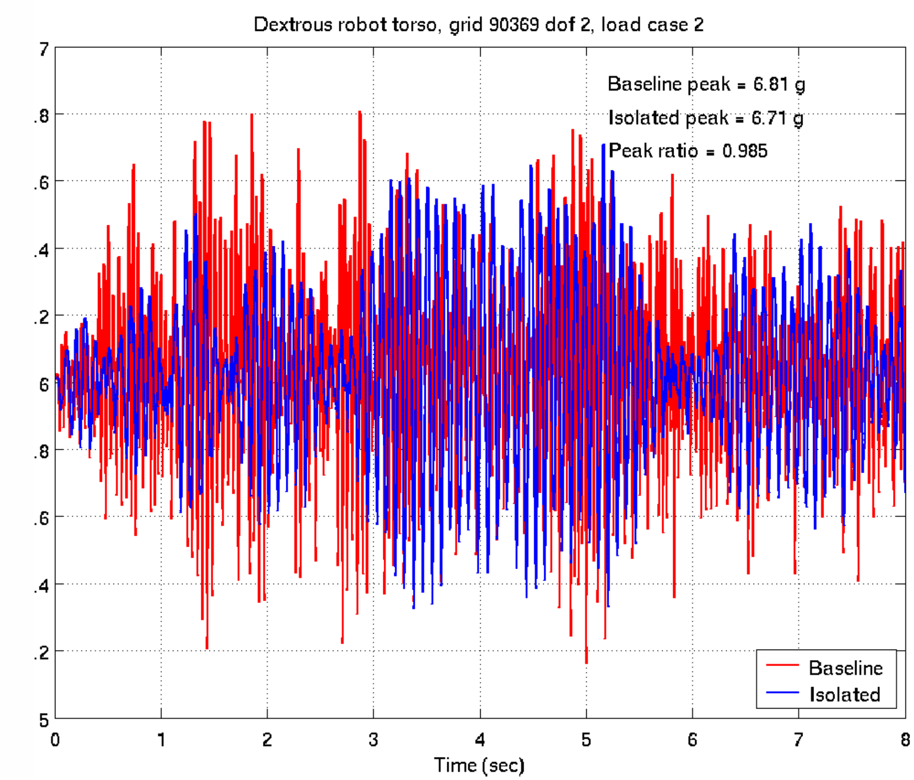
* = Results shown for November 2004 Trade Study Model

*PREDICTED** HRV Flight Loads – Max G

Wide Field Camera



Dexterous Robot Torso



-> Response is dominated by 6 G Vehicle Thrust. No Mitigation from Isolation System for this flight case

* = Results shown for November 2004 Trade Study Model

2 Pronged Approach to HRV Flight Loads

Sensitive HRV component

Dynamic Flight Load Case → Load Isolation

Max-G Flight Load Case → Launch Vehicle "Throttle Back"

Launch Vehicle Throttle Back Progress

- Face to face TIM at KSC identified the need to conduct Launch Vehicle performance analyses to determine our options for “Max-G” loads reduction.
- KSC has in-house capability to provide this analyses.
- Additional information has been provided by launch vehicle vendors which shows that a reduction in the max-G static loads will be possible

November 2004 Basedrive Results - Liftoff

	Hard Mount	RSS	Isolated	RSS	% Change	Allow
PAF Base Moment In-Lb RX-Dir	3.4.E+07		7.7.E+06		-77%	
PAF Base Moment In-Lb RZ-Dir	1.9.E+07		7.9.E+06		-58%	
HRV Net CG Accel G X-Dir	2.7		1.9		-30%	
HRV Net CG Accel G Y-Dir	1.7		2.1		23%	
HRV Net CG Accel G Z-Dir	4.5		1.5		-66%	
HRV Net CG Accel Rad/s2 RX-Dir	18.1		7.2		-60%	
HRV Net CG Accel Rad/s2 RY-Dir	7.6		6.4		-15%	
HRV Net CG Accel Rad/s2 RZ-Dir	10.8		9.0		-17%	
EM Net CG Accel G X-Dir	3.2		1.6		-50%	
EM Net CG Accel G Y-Dir	1.9		2.4		27%	
EM Net CG Accel G Z-Dir	5.9		1.5		-74%	
EM Net CG Accel Rad/s2 RX-Dir	22.0		11.1		-50%	
EM Net CG Accel Rad/s2 RY-Dir	8.7		7.2		-18%	
EM Net CG Accel Rad/s2 RZ-Dir	12.2		11.8		-3%	
GA Net CG Accel G X-Dir	3.0		2.0		-33%	
GA Net CG Accel G Y-Dir	2.9	7.5	3.2	4.7	12%	
GA Net CG Accel G Z-Dir	6.2		2.7		-56%	
DR Net CG Accel G X-Dir	3.9		1.9		-51%	
DR Net CG Accel G Y-Dir	3.2	8.4	3.0	3.8	-9%	
DR Net CG Accel G Z-Dir	6.7		1.3		-80%	
WFC3 Net CG Accel G X-Dir	3.9		3.1		-22%	
WFC3 Net CG Accel G Y-Dir	4.5	8.3	4.5	6.1	0%	6.7
WFC3 Net CG Accel G Z-Dir	5.7		2.7		-52%	
FGS Net CG Accel G X-Dir	3.4		1.4		-57%	
FGS Net CG Accel G Y-Dir	3.0	7.4	2.8	3.5	-6%	5.9
FGS Net CG Accel G Z-Dir	5.8		1.4		-76%	
COS Net CG Accel G X-Dir	3.8		1.4		-62%	
COS Net CG Accel G Y-Dir	3.7	8.9	3.6	4.4	-3%	8.0
COS Net CG Accel G Z-Dir	7.1		2.1		-71%	

-> Major Component Loads Below Requirements with isolation system

November 2004 Loads Results – Max G

	Hard Mount	RSS	Isolated	RSS	% Change	Allow
PAF I/F Frc Grid 95000 In-Lb RX-Dir	7.2.E+05		6.1.E+05		-15%	
PAF I/F Frc Grid 95000 In-Lb RZ-Dir	9.3.E+05		9.7.E+05		5%	
HRV Net CG Accel G X-Dir	0.1		0.2		57%	
HRV Net CG Accel G Y-Dir	6.4		6.7		4%	
HRV Net CG Accel G Z-Dir	0.1		0.1		-1%	
HRV Net CG Accel Rad/s2 RX-Dir	0.5		0.5		-11%	
HRV Net CG Accel Rad/s2 RY-Dir	2.1		1.8		-12%	
HRV Net CG Accel Rad/s2 RZ-Dir	0.7		0.8		17%	
EM Net CG Accel G X-Dir	0.1		0.2		28%	
EM Net CG Accel G Y-Dir	6.4		6.8		5%	
EM Net CG Accel G Z-Dir	0.2		0.1		-21%	
EM Net CG Accel Rad/s2 RX-Dir	1.1		0.8		-26%	
EM Net CG Accel Rad/s2 RY-Dir	2.3		2.0		-12%	
EM Net CG Accel Rad/s2 RZ-Dir	1.2		1.2		0%	
GA Net CG Accel G X-Dir	0.4		0.3		-13%	
GA Net CG Accel G Y-Dir	6.6	6.6	6.9	6.9	5%	
GA Net CG Accel G Z-Dir	0.6		0.5		-17%	
DR Net CG Accel G X-Dir	0.4		0.3		-23%	
DR Net CG Accel G Y-Dir	6.5	6.5	6.8	6.8	4%	
DR Net CG Accel G Z-Dir	0.2		0.2		-21%	
WFC3 Net CG Accel G X-Dir	0.5		0.6		14%	
WFC3 Net CG Accel G Y-Dir	6.6	6.6	7.0	7.0	6%	6.7
WFC3 Net CG Accel G Z-Dir	0.7		0.3		-59%	
FGS Net CG Accel G X-Dir	0.4		0.3		-39%	
FGS Net CG Accel G Y-Dir	6.9	6.9	6.9	6.9	1%	5.9
FGS Net CG Accel G Z-Dir	0.4		0.3		-41%	
COS Net CG Accel G X-Dir	0.5		0.4		-32%	
COS Net CG Accel G Y-Dir	8.0	8.0	7.2	7.3	-9%	8
COS Net CG Accel G Z-Dir	0.9		0.6		-33%	

-> Throttle Back may be required to alleviate high G loads

November 2004 Results - DR

- Results shown for worst case DR joint loads from November CSA Basedrive runs.

	in-lbs		in-lbs			in-lbs
	Hard Mount	M.S.	Isolated	M.S.	% Change	Allow
DR Pitch/Roll/Yaw Joint Moment Liftoff	16168	-0.20	7016	0.83	-130%	12857
DR Pitch/Roll/Yaw Joint Moment Max G	14048	-0.08	14548	-0.12	3%	12857
DR Pitch/Roll/Yaw Joint Torque Liftoff	6442	0.00	1765	2.64	-265%	6429
DR Pitch/Roll/Yaw Joint Torque Max G	3914	0.64	3986	0.61	2%	6429
Allowable has 1.4 Safety Factor						

-> Basedrive results for DR confrim that (1) isolation is necessary and (2) throttle back may be necessary

Isolation System Complexities

- Isolation System Requires careful system level analysis involving payload, launch vehicle, and isolation system vendor
  - Initial conversation with KSC/ Launch Dynamics (March 04) were positive toward our design
    - Previous experience with OSP Program using a 4 Hz and a 2.5 Hz low frequency system with a 60,000 pound payload
    - Flight control interaction needs a system
  - KSC expects that PPG Design Load Factors are sufficient for preliminary design.
  - Linearity of isolation system needs to be characterized.
    - Generally temperature dependence of VEM is well known

Summary

- The isolation system design appears to work as planned
  - Liftoff load case predictions within requirements for instruments
  - Max G load case results highlight the need for G-load mitigation
- CSA Basedrive analyses validate PDR level design of HRV
  - models will be sent to KSC for full CLA